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Global convergence in per capita CO_2 emissions

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ABSTRACT

Climate change is now widely recognized as the major environmental problem. In order to reduce CO_2 emissions so as to cope with climate change, a wide range of effective policies, and an enforced international cooperation are required. A better understanding of the dynamic changes of CO_2 emissions will strengthen international cooperation and provide necessary information for policy making. This paper investigates the global convergence in per capita CO_2 emissions over the period 1971–2008. The results manifest an absolute convergence within subsamples grouped by income level, while provide little evidence of absolute convergence in the full sample containing 110 countries. Furthermore, this paper takes the GDP per capita into consideration within the conditional convergence framework. Interestingly, the result shows that, within different income groups, the relationships between GDP per capita and per capita CO_2 emission growth are different. Specially, per capita CO_2 emissions of high-income countries keep at the "steady state" as income rises. This result is contrary to Environmental Kuznets Curve, which indicates that the CO_2 emissions will decline when income rises beyond a certain level.

Contents

1. Introduction

Climate change is becoming one of the most severe challenges facing human society in the 21st century. It is crucial to cut down the CO_2 emissions so as to reduce the atmospheric concentration of greenhouse gases (GHGs). Due to the externality of mitigation, many countries put the emphasis of argument on who should undertake the obligation of mitigation and how much CO_2 emissions should be deducted. According to Kyoto Protocol, during the period over 2008–2012 Annex I countries (36 industrial countries in transition are listed in Annex I in United National Framework Convention on Climate Change) commit to reduce their collective greenhouse gas emissions by 5.2% from the 1990 level; developing countries like China and India with larger emissions were not required to reduce emission levels. However, the Bush government in 2001 refused to fulfill the Kyoto Protocol Requirement because of three reasons: the first reason is that the science underlying climate change is highly uncertain, the second reason is mandatory reduction targets may undermine

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economic growth and weaken the US' competitiveness, and the last reason is that India and China should be involved in the negotiation [1]. Russia officially signed on the Kyoto Protocol in October 2004, and then the Kyoto Protocol came into force on 16 February, 2005. However, since the Kyoto Protocol set no targets on developed countries for reducing their CO_2 emissions beyond 2012, how to continue the second commitment period under the Kyoto Protocol after 2012 became an important issue to tackle global warming. In 2007, Bali Roadmap charted the course for the international climate negotiations and the deadline for negotiators to work out the post-2012 plans, but in 2009 Copenhagen conference, the developing and developed countries came at loggerheads again on the allocation of responsibilities and obligations. The developing countries insisted on simultaneously executing both UNFCCC (United Nations Framework Convention on Climate Change) and Kyoto Protocol, while developed countries required that developing countries make and carry out measurable, reportable, verifiable commitments and actions. The summit ended in an agreement of non-binding Copenhagen Accord. In Cancun climate conference, the negotiator agreed to set the Green Climate Fund, which pledged to provide poor countries with additional money to bolster their anti-warming and adaption efforts, but the issues such as the timeframe for the second commitment period of Kyoto Protocol was not decided. Durban conference has a special significance as the first commitment period of Kyoto Protocol would expire next year. However, only the EU among major developed countries agreed to stay in Kyoto before the conference, Japan, Russia and Canada had all dropped out, US still refused to accept binding targets. After a two-weeks marathon of talks, negotiators reached a last-minute agreement on a new climate deal known as the Durban platform for enhanced action, whereby both developed and developing countries promise to work on an agreement that should be legally binding on all parties, to be agreed by 2015 and come into effect from 2020. Doha is the last opportunity to draw up a working plan for the new global climate treaty and start the second commitment period, but no progress has been made at this conference, no new agreement to limit the greenhouse-gas emissions and no deal on new funds to help poor countries adapt.

In fact, a full understanding of “common but differentiated responsibilities” on mitigation is necessary for the international negotiation and cooperation. A concise identification of emission right and a better understanding of the dynamic changes of per capita CO_2 emissions are both urgently needed to advance international cooperation between developed and developing countries. Therefore, research on the convergence of per capita CO_2 emissions shows great significance not only in promoting international cooperation but also in formulating effective mitigation policies.

The concept of convergence originates from Solow's Neoclassical Growth Model. It indicates that backward area will keep developing faster than the developed area until the gap between the two regions vanishes, and finally the economic growth of each region keeps at a steady state. According to the convergence theory adopted by many literatures on income growth, if the time series of per capita CO_2 emissions shows a trend of convergence, every person in the world should have an equal share of CO_2 emission rights [2]. Historically, the developed countries are actually the major contributors to the current global warming. They should take the leading role in CO_2 emission reduction. On the other hand, the existence of convergence indicates that the CO_2 emissions increments will mainly come from the developing countries, which implies that, developing countries should also take actions to cut down the growth of their emissions. Only in that way, we can achieve the goal of controlling the world average temperature rise under 2 centigrade. Furthermore, a large number of researches have shown that CO_2 emissions within a country are closely related to its economic growth, industrialization, urbanization, population structure, and technology level ([3–11]). If this view is applied to developing countries like China, emission reduction in these countries would be at the cost of slowing down the economic growth, industrialization and urbanization. In this regard, it is unaffordable and unfeasible for them to compulsively fulfill the carbon mitigation task. Hence developed countries, enjoyed the advantage position in terms of funds and technologies, they also have the responsibility to provide supports to developing countries for emission reduction [12].

However, are the per capita CO_2 emissions of different countries convergent? Using different methods and samples, different results are obtained. [13–17] demonstrated that the CO_2 emissions of the OECD (Organization for Economic Co-operation and Development) countries showed a convergence, while [18] suggested that per capita CO_2 emissions of OECD countries experienced divergence during the observation period. [19–22] found strong evidence of convergence worldwide; however, some other researches proved the divergence of per capita CO_2 emissions, e.g., [14].

In order to investigate the convergence of per capita CO_2 emissions worldwide, dynamic changes of per capita CO_2 emissions over the period 1971–2008 are analyzed in this paper. The results indicate that there is no absolute convergence within the full sample of 110 countries, but there exists club convergence within subsamples which are grouped by income level. Motivated by this result, under the conditional convergence framework, we further study the relationship between per capita GDP and per capita CO_2 emissions, and try to depict the convergent path of per capita CO_2 emissions. The rest of the article is organized as follows. Section 2 describes the previous studies related to the convergence of CO_2 emissions. Section 3 investigates the absolute convergence of per capital CO_2 emissions. The relationship between GDP per capita and the per capita carbon emissions is analyzed in Section 4. The last section provides conclusion and policy recommendations.

2. Empirical literature

CO_2 emissions are considered as the main cause of climate change. A good understanding of the dynamic changes of CO_2 emissions is necessary for policy making. Also, efficient policy measures are needed to accomplish CO_2 mitigation and address the climate change. Besides, a good understanding of the dynamic changes of CO_2 emissions can also help developing countries seize the initiative in multilateral negotiation on climate change. Therefore, lots of recent empirical studies focused on the convergence of per capita CO_2 emissions.

The first study on CO_2 emission convergence was carried out by [13]. It tested the stochastic and conditional convergence of CO_2 emissions within the group of 21 industrialized countries, and the results of both panel unit root test and cross-sectional regressions verified the existence of convergence. Using the data of OECD sample, [23] found similar results as [13]. However, we can say that the result of [13] is unreliable. One reason is that [13] assumed the individual country is independent, and second is that it adopted a relatively short span of data. Thus, in an attempt to overcome the inaccuracies in [13], [17] employed the panel unit root tests that allowed for cross-sectional dependence. By this method, [17] tested the CO_2 emission convergence within both the group of developed countries and the group of developing countries respectively. Results indicated that per capital CO_2 emissions showed a convergence within each of the two country groups. Similarly, [16] provided strong evidence that supports both the stochastic and deterministic convergence in 23 OECD countries over the years 1960–2002. Applying the panel data test method developed by Carrion-i-Silvestre et al., [27] illustrated the more obvious convergence in per capita CO_2 emissions among OECD countries when considering the policy interventions. [22] verified the existence of absolute convergence in per capita CO_2 emissions

within the group of 22 European countries, and found that the convergence speeds of these countries were different. What deserves special mention is that, [22] is the first study that evaluated the relationship between CO_2 emissions speed and the proportion of industry value-added in GDP.

Similar results emerge in the case of world sample. [24] adopted the method of dynamic stochastic kernel estimation to study the convergence of CO_2 emissions per capita within a sample group of 97 countries. The results suggested that the cross-country distribution of per capita emissions was characterized by persistence, but there was little evidence of absolute convergence in per capita emissions. [25] verified a decrease in disparities of CO_2 emissions among a set of 87 countries. [21] found that the carbon emissions of 128 countries were convergent over the period 1960–1985. [21] also carried out further analysis on the phenomenon of club convergence over the period 1975–2003. The results revealed that 91 of those countries converged slowly, while the other 37 countries converged relatively faster, and the two country groups eventually converged at different steady states.

Completely different conclusions are also derived by some researches. [18] carried out the stationary and unit root tests that allowed for cross-sectional dependency, and the results showed that per capita CO_2 emissions did not converge among OECD countries during the observation period of 1950–2002. [19] found little evidence of convergence within the full sample (100 countries) either. Focusing on a 88-countries sample over 1960–2000, [14] derived the statistical distribution of data and carried out the σ-convergence analysis and DF-GLS unit root tests. The results supported the divergence of emissions among the sample countries. Based on the analysis of Markov chain transition matrix, [14] also predicted that divergence trend would continue in the next five decades; but for the later 100 years, the CO_2 emissions of these countries might show a convergence. Similarly, using the method of non-parametric approach, [25] showed that the disparities in per capita CO_2 emissions across 87 countries decreased during 1960–99. In order to testify the assumption that income convergence serves as the sufficient condition for the convergence of per capita CO_2 emissions, [26] studied the CO_2 emission convergence among the US states. The results confirmed the convergence of per capita income, while suggested stark divergence in production-based per capita CO_2 emissions, and indicated no evidence for convergence of consumption-based per capita CO_2 emissions.

According to the literature mentioned above, it is obvious that research results are diverse when adopting different methods and data. Whether per capita CO_2 emissions converge or not is still inconclusive. Most of the studies focusing on the convergence issue just estimated the per capita emissions or tested the stationary of the data. Few of these studies have carried out comprehensive investigations and paid attention to the pathway, the steady state value, or the influencing factors of convergence. In addition, the studies focusing on the world sample are particularly rare. Therefore, in order to provide more information on distribution and characteristics of CO_2 emissions worldwide, CO_2 convergence is investigated in this paper with the help of new statistical methods.

3. Model and data

3.1. Model

Generally, three measures of convergence, σ-convergence, β-convergence, and stochastic convergence are commonly adopted when analyzing gaps in per capita CO_2 emissions among countries. The σ-convergence tests the convergence by identifying whether the standard deviation among a group of countries decreases over time. The requirement of this method is relatively more strict [28]. Particularly, the existence of convergence will be rejected due to the permanent difference among individuals caused by an external shock. Stochastic convergence is another widely used method. It tests whether the time series data of relative emissions per capita (the ratio of per capita CO_2 emissions of one country to the world average level) are stationary. If the time series emission data are characterized by a unit root, the impacts of external shocks on emissions are permanent and per capita CO_2 emissions are not convergent; otherwise, the data are stationary over time and the impacts of the shocks on emissions are temporary [14]. β-convergence seeks to determine whether a “catch-up” process happens. The “catch-up” process means that, countries with initially lower levels of CO_2 emission per capita would experience higher growth in per capita CO_2 emissions, and eventually both the high-emission and low-emission countries just converge to the same emission level. σ-convergence is a kind of strong convergence, and β-convergence is a necessary condition for the σ-convergence. This means that the per capita CO_2 emissions of initially low-emission countries will increase faster given that all countries' emission levels would finally tend towards the same level.

Among these three methods, only the β-convergence can provide comprehensive information regarding the future distribution of per capita CO_2 emissions. Specifically, the information includes the equilibrium emission level, the speed of CO_2 emissions returning to that equilibrium level and the relationship between per capita CO_2 emissions and other factors like per capita income. Therefore, this paper would adopt the β-convergence test.

β-convergence will be tested by regressing the average growth rate on initial value of the growth rate. If the coefficient resulted is positive and statistically significant, it is interpreted as the evidence of β-convergence. β-convergence can be classified into absolute and conditional convergence according to whether or not the control variables are included. The absolute convergence indicates that there is an identical growth path and steady state for all countries in the long-term, no matter the individual difference on industry structure, energy consumption structure, policies and more. The absolute convergence is modeled as:

$$\frac{1}{T}\left[\ln\left(\frac{E_{i,t+T}}{E_{i,t}}\right)\right] = \alpha - \frac{1}{T}(1-e^{-\beta T})\ln E_{i,t} + \varepsilon_{i,t} \quad (1)$$

where i, means the ith economic entity; t, denotes the time; T, means the length of the period; $E_{i,t}$, represents the initial level of CO_2 emissions per capita; $E_{i,t+T}$, denotes the emission level at the end of the period; β, is the convergence speed, a significant and positive β implies the absolute convergence in the tested region during period T; $\varepsilon_{i,t}$, is the stochastic error term.

Because Model (1) only selects data of two time points, the initial and the final periods of the empirical study, the information between the two points is left out. Therefore, in order to make full use of the data information, we reconstruct Model (1) into a dynamic model:

$$\left[\ln\left(\frac{E_{i,t}}{E_{i,t-1}}\right)\right] = \alpha - (1-e^{-\beta})\ln E_{i,t-1} + \varepsilon_{i,t} \quad (2)$$

According to Model (2), if β is significant and positive, the distribution of per capita CO_2 emissions can be assumed to follow the process as

$$\ln E_{i,t} = \alpha + e^{-\beta}\ln E_{i,t-1} + \varepsilon_{i,t} \quad (3)$$

E_0 represents the emission level that all countries' per capital emissions converge to. T denotes the time periods required by countries with lower per capita CO_2 emissions to catch up with countries initially with higher per capita CO_2 emissions.

$$E_0 = e^{\frac{\alpha}{1-e^{-\beta}}} \quad (4)$$

$$T = \ln\frac{2}{\beta} \tag{5}$$

Different from absolute convergence method, conditional convergence method considers the impacts of individual difference on per capita CO_2 emissions. Thus, it introduces control variables like per capita income, industry structure, and urbanization level into model (2). The existence of absolute convergence among countries also indicates the existence of conditional convergence. The conditional convergence model is:

$$\left[\ln\left(\frac{E_{i,t}}{E_{i,t-1}}\right)\right] = \alpha - (1 - e^{-\beta})\ln E_{i,t-1} + \gamma x_{i,t} + \varepsilon_{i,t} \tag{6}$$

where is the $x_{i,t}$, denotes the control variable.

3.2. Data

In the part of the empirical analysis on absolute convergence, we adopt the data of per capita CO_2 emissions over 1971–2008, collected from International Energy Agency (IEA). The global group includes 110 countries. These countries are grouped into low-income countries, lower-middle-income countries, upper-middle-income countries and high-income countries, according to the Indicators Database of World Bank. These countries are listed in Table 1, and the number of countries in each group selected for the study is based on data availability.

In the part of empirical analysis on conditional convergence, GDP per capita is selected as the control variable. To achieve full comparability of the GDP among the countries, the GDP of each country should be adjusted by the nominal exchange rate or purchasing power parity. In this paper, we use the GDP data which have already been adjusted by IEA based on the Purchasing Power Parity (PPP).

4. Empirical results

4.1. Absolute convergence

Lagged term of dependent variable $E_{i,t-1}$ is included as an independent variable on the right hand side of model (2) and model (6). Thus, biased results can be derived when adopting the least squares estimate or the standard fixed effect model. It is because that in those two models, the independent variables are correlated with the past and possibly the current realizations of error term. Instrumental variable estimates (IV) and Generalized method of moments (GMM) estimates have been proven to be effective when addressing the correlation between $E_{i,t-1}$ and $\varepsilon_{i,t}$. GMM estimates have been adopted in numerous studies in recent years. Two methods of GMM estimates are commonly used. One is called "difference GMM", which is put forward by [29]. The "difference GMM" starts with data transformation, usually by differencing and then employing the lagged dependent variables as instrumental variables. But it has one disadvantage, which is that it would generate invalid estimates when the coefficients of the lagged dependent variables are close to 1 or the data sample is moderately small. Based on the research of Arellano and Bover, [30] assumed that the first differences of instrument variables are uncorrelated with the fixed effects, and the introduction of more instrumental variables is allowed [31]. They proposed "system GMM", in which, the lagged level variables are employed as the Instrumental variables (IVs) of the first-order difference equation, while the first-order difference variables are also used as the IVs of the level equation. Results of the system GMM have been proven to be more valid.

It is worth noting that both difference GMM and system GMM are designed for situations with "small T, large N" panels. In this paper, since only the world sample's time dimension is shorter than the individual dimension, method of system GMM is applied to estimate the per capita CO_2 emission convergence of the world sample.

[32] adopted a Monte Carlo approach to compare the performance of ordinary least squares (OLS), the least squares dummy variable estimates (LSDV), Anderson-Hsiao (AH) estimates, one-step GMM estimates, and two-step GMM estimates. The results indicate that, as the time dimension of the panel increases, the AH estimates perform equally well while the other estimates do not. Specifically, when $T=30$, $N=20$, $\gamma=0.8$, the estimation bias of γ using AH is much smaller than that of using OLS, LSDV, and GMM. Besides, the individual dimensions of the low-income countries, lower-middle-income countries, upper-middle-income countries, and high-income countries are respectively 15, 29, 24, and 42, and the time dimensions of each group is 38. So AH method is applied here to estimate the convergence of per capita CO2 emissions for these four groups.

Table 1
Country categorization.

Low-income countries	Bangladesh	Benin	Dem. Rep. of Congo	Ethiopia	Ghana
	Haiti	Kenya	DPR of Korea	Mozambique	Myanmar
	Nepal	Togo	Zambia	Zimbabwe	United Rep. of Tanzania
Lower- and middle-income countries	Angola	Bolivia	Cameroon	China	Congo
	Côte d'Ivoire	Ecuador	Egypt	El Salvador	Guatemala
	Honduras	India	Indonesia	Iraq	Jordan
	Morocco	Nicaragua	Nigeria	Pakistan	Paraguay
	Philippines	Senegal	Sri Lanka	Sudan	Syrian Arab Republic
	Thailand	Tunisia	Vietnam	Yemen	
Upper- and middle-income countries	Albania	Algeria	Argentina	Brazil	Bulgaria
	Chile	Colombia	Costa Rica	Cuba	Dominican Republic
	Gabon	Islamic Rep. of Iran	Jamaica	Lebanon	Malaysia
	Mexico	Panama	Peru	South Africa	Uruguay
	Venezuela	Libyan Arab Jamahiriya	Romania	Turkey	
High-income countries	Netherlands	Bahrain	Kuwait	Oman	Qatar
	Saudi Arabia	United Arab Emirates	Trinidad and Tobago	Canada	United States
	Hong Kong	Australia	New Zealand	Brunei Darussalam	Singapore
	Japan	Korea	Cyprus	Gibraltar	Malta
	Austria	Belgium	Czech Republic	Denmark	Finland
	Germany	Greece	Hungary	Iceland	Ireland
	United Kingdom	Luxembourg	Norway	Poland	Portugal
	Slovak Republic	Sweden	Switzerland	Italy	Spain
	Israel	France			

A crucial assumption for the validity of GMM estimates is that the instrumental variables are exogenous [31], so it is necessary to test the validity of instrumental variables via Sargan/Hansen test and autocorrelation test. As described in Table 2, the P value of AR (2) test for each group is over 10% and the P value of Hansen test also reaches 1, which means, the instrumental variables for the model of each group are effective.

Table 2 reports the estimated value of β, together with the corresponding t statistic. All results imply that the coefficients of model with either short or long panel are statistically insignificant. This indicates that, when adopting the system GMM approach, the results provide no evidence supporting the existence of absolute convergence within the world sample. Specifically, during the period of 1971–1990, the negative β coefficient illustrates that the per capita CO_2 emissions are divergent among these countries. This result confirms the earlier findings of [13,14,19,21].

In this part, we divide the world sample into four groups according to per capita gross national income. The results here indicate that there is evidence of convergence within subgroups. Besides, the convergence of different subgroups has different steady states and different convergence rates. Such a convergence pattern is usually called “club convergence”.

Club convergence means that convergence of per capita CO_2 emissions exists within the subgroup in which countries sharing common economic or geographical characteristics, but does not exist within the full group. The existence of the club convergence implies that different sub country groups will converge to different steady states. As shown in Table 3, β of each subgroup is positive and significant, but their steady states are different. Specifically, the high-income country group experiences the highest convergence speed among all four groups, and it also has the highest steady state level (14.3 t of CO_2 emissions per capita). Per capita CO_2 emissions of the upper-middle-income countries also show relatively faster convergence speed. It will finally fluctuate around 5.90 t, lower than that of the high-income group, but higher than that of the low-income group (0.26 t) and the lower-middle-income group (4.17 t).

What deserves special mention is that, the convergence of the low-income country group is mainly attributed to the emission reduction of countries initially with high level of per capita CO_2 emissions. Such phenomenon does not exist in the other groups. Fig. 1 describes the dynamic changes of per capita CO_2 emissions in low-income countries over the period of 1971–2008. The per capita CO_2 emissions in DPR of Korea had the highest initial level among the low-income countries. It increased from 4.61 t in 1971 to a peak of 6.75 t in 1985, and then dropped to 2.91 t in 2008. In addition, the dynamic changes of per capita CO_2 emissions in Zimbabwe and Zambia showed similar trace as that of DPR of Korea. Per capita CO_2 emissions in Dem. Rep. of Congo, Kenya, and Mozambique have experienced a decreasing trend since 1971. However, the per capita CO_2 emissions of the other countries showed a continuous increase, but most of their emission levels were below 0.4 t. In addition, this phenomenon can also be supported by the downward trend of average level of per capita CO_2 emissions, which was 0.59 t in 1971 and then dropped to 0.42 t in 2008.

4.2. Conditional convergence

The results of absolute convergence analysis indicate that the per capita CO_2 emissions of 110 countries show significant divergence, but there is evidence of club convergence. In addition, the steady state of per capita CO_2 emissions is closely related to the income level. Therefore, in order to analyze the impact of income level on per capita CO_2 emissions, we employ GDP per capita as a control variable and set up a conditional convergence model. The estimated results are shown in Table 4.

As Table 4 shows, both the results of AR test and Hansen test verify the effectiveness of the IVs. The coefficient of GDP per capita is found to be significant and positive. We can see that 1% rise of GDP per capita would result in 0.0163% increase in the growth rate of per capita CO_2 emissions. Meanwhile, the convergence speed, β, is also positive and statistically significant. This means, when GDP per capita is considered, convergence does exist in the world group. Generally, we can draw the conclusion that GDP per capita has a significant impact on the convergence of per capita CO_2 emissions.

The Environmental Kuznets Curve (EKC) suggests an inverted-U relationship between pollution and income per capita. In the early stage, rapid economic growth accompanies environmental degradation. When a country stands on certain income level, its further economic growth will bring environmental improvement. In an attempt to reexamine the empirical evidence of Environmental Kuznets Curve, we would like to evaluate the impact of GDP per capita on per capita CO_2 emissions respectively for the four subgroups. The analysis will be carried out under the conditional convergence framework.

As described in Table 5, all β are positive and statistically significant. Compared to the convergence speed obtained under absolute convergence framework, the convergence rates here

Table 3
Test on the absolute convergence in per capita CO_2 emissions within each subgroup.

	Low-income countries	Lower- and middle-income countries	Upper- and middle-income countries	High-income countries
β	0.0157 (172.40)	0.0046 (327.44)	0.0160 (216.29)	0.0307 (302.02)
con.	−0.0208 (−1.74)	0.0066 (8.25)	0.0283 (5.59)	0.0817 (11.23)
E_0	0.26	4.17	5.90	14.3
T	44	149	36	22

Table 2
Test on the absolute Convergence in per capita CO_2 emissions within the world group.

	1971–2008	1980–2008	1990–2008	1971–1990	1971–2000
β	0.0026 (0.359)*	0.0015 (0.700)*	0.007 (0.192)*	−0.0057 (0.239)*	0.0032 (0.421)*
con.	0.0098 (0.188)*	0.0084 (0.274)*	0.0138 (0.082)*	−0.0148 (0.228)*	0.0065 (0.441)*
The *P* value of AR(2) test	0.36	0.77	0.34	0.16	0.27
The *P* value of Hansen test	1	1	1	1	1

* denotes the *P* value of *t* test

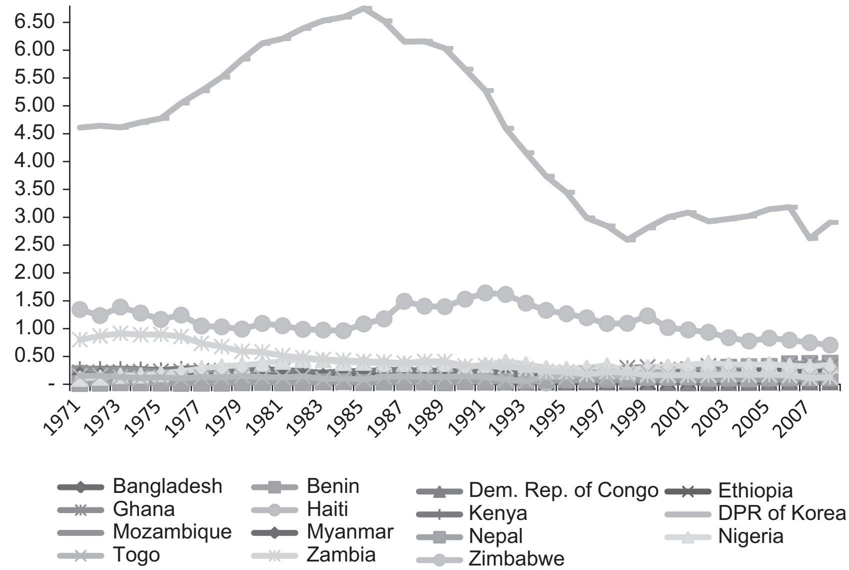

Fig. 1. CO_2 emissions per capita in low-income countries.

Table 4
Test on the Conditional Convergence within the world group.

	β	lny	The *P* value of AR (2) test	The *P* value of Hansen test
world group	0.0120 (−4.00)	0.0163 (3.56)	0.38	1

Table 5
Test on the conditional convergence within each subgroup.

	Low-income countries	Lower and middle-income countries	Upper and middle-income countries	High-income countries
β	0.0229 (144.98)	0.0057 (309.00)	0.0240 (203.51)	0.0315 (265.82)
lny	0.0360 (1.99)	0.0089 (1.89)	0.0401 (4.6)	0.0007 (0.14)
con.	−0.0381 (−2.57)	0.0152 (2.93)	−0.0392 (−2.58)	0.0803 (6.25)

remarkably raised. Results obtained under absolute convergence framework and conditional convergence framework all indicate that convergence exists within each subgroup.

Moreover, the estimated coefficients of GDP per capita reveal the fact that the impacts of GDP per capita on the growth rate of CO_2 emissions per capita are diverse among groups. As to the low-income countries, lower-middle-income countries, and the upper-middle-income countries, the positive correlation between GDP per capital and the growth rate of per capita CO_2 emissions indicates that the speed-up of CO_2 emission growth will accompany the rapid economic growth. Specifically, the coefficient of GDP per capita in upper-middle-income countries amounts to 0.0401, higher than other subgroups. However, as in high-income country group, GDP per capita imposes a positive but limited impact on per capita CO_2 emissions, since the coefficient is positive but insignificant; which implies, CO_2 emissions per capita will increase as income rises and arrive at a "steady state" when GDP per capita reaches a certain level. This is distinct from the inverted U-shaped path which describes that per capita CO_2 emissions will decline when income goes beyond the certain level.

5. Conclusion

According to the report of the UN Environment Program, levels of greenhouse gas emissions are now 14% above where they need to be in 2020 if the target of capping the temperature rise below 2 degrees is to be made. More actions to cut the CO_2 emissions need to be done. Better understanding the dynamic changes of CO_2 emissions will provide more information for policy making, and as well promote better international cooperation, such as negotiation between the developed countries and developing countries.

Based on the data over the period 1971–2008, this paper focuses on two important issues. First, we sought whether per capita CO_2 emissions of countries worldwide show similar convergent pattern. To answer this question, an absolute convergence approach is employed. The results provide little evidence for absolute convergence in the full sample containing 110 countries, but the per capita CO_2 emissions of countries with similar income characters (which form a subgroup) show obvious convergence. Based on these results, this paper further studies the second issue; which is, whether there exists relationship between the GDP per capita and growth rate of CO_2 emissions per capita. Our results indicate that the per capita CO_2 emissions among these countries present conditional convergence, and the increase of GDP per capita can raise the growth rate of per capita CO_2 emissions in country groups except in the high-income group. In addition, these impacts of GDP per capita on per capita CO_2 emissions are diverse in different country groups.

Based on the results above, two conclusions can be reached. Firstly, the existence of conditional convergence in the world sample implies that per capita CO_2 emissions of countries with same income level are convergent. Therefore, the allocation of emission credit should be based on GDP per capita rather than on total GDP, and countries with similar GDP per capita should have an equal share of carbon emission rights. Secondly, the future increment of CO_2 emissions will mainly come from the developing countries. Specifically, the growth rate of per capita CO_2 emissions in upper-middle-income countries will increase by 0.04% as GDP per capita increases by 1%. In addition, it is worth noting that the impact of GDP per capita on per capita CO_2 emissions in lower-middle-income countries (which includes China and India) is weaker than that in low-income countries and upper-middle-income countries.

How to read these two conclusions? In order to achieve the CO_2 mitigation target, it is necessary to cut down CO_2 emissions of both developed and developing countries. However, in different economic development stages, the macroeconomic impact of carbon mitigation are diverse, and the abatement costs are also different. Developed countries' experience tells that energy consumption is rigid during the process of industrialization and urbanization. The developing countries are still in the stage of accelerating industrialization and urbanization. One characteristic of this stage is that heavy industry plays as the major driver of economic growth. This implies that energy efficiency in developing countries is lower. Rapid economic growth combined with lower energy efficiency would lead to rigid increment of CO_2 emissions. With limited funds and technologies, these developing countries would suffer the slow-down of industrialization and urbanization when reducing CO_2 emissions. Historically, developed countries are actually the main contributor of the human-produced CO_2 emissions. Thus, they should bear more responsibility of mitigation. Besides, as those countries have completed the industrialization and urbanization, the correlation between CO_2 emission growth and GDP increase is insignificant. Moreover, the effect of mitigation on economic growth in those countries is smaller than that in the developing countries. Therefore, developed countries should help developing countries to reduce CO_2 emissions by providing them with funds and technologies. Simultaneously, they should also do more for reduce their own CO_2 emissions.

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